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## Neutron imaging of alkali metal heat pipes

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**Abstract**

High-temperature heat pipes are two-phase, capillary driven heat transfer devices capable of passively providing high thermal fluxes. Such a device using a liquid-metal coolant can be used as a solution for successful thermal management on hypersonic flight vehicles. Imaging of the liquid-metal coolant inside will provide valuable information in characterizing the detailed heat and mass transport. Neutron imaging possesses an inherent advantage from the fact that neutrons penetrate the heat pipe metal walls with very little attenuation, but are significantly attenuated by the liquid metal contained inside.

Using the BT-2 beam line at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, preliminary efforts have been conducted on a nickel-sodium heat pipe. The contrast between the attenuated beam and the background is calculated to be approximately 3%. This low contrast requires sacrifice in spatial or temporal resolution so efforts have since been concentrated on lithium (Li) which has a substantially larger neutron attenuation cross section.

Using the CG-1D beam line at the High Flux Isotope Reactor (HFIR) of Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, the first neutron images of high-temperature molybdenum (Mo)-Li heat pipes have been achieved. The relatively high neutron cross section of Li allows for the visualization of the Li working fluid inside the heat pipes. The evaporator region of a gravity assisted cylindrical heat pipe prototype 25 cm long was imaged from start-up to steady state operation up to approximately 900°C. In each corner of the square bore inside, the capillary action raises the Li meniscus above the bulk Li pool in the evaporator region. As the operational temperature changes, the meniscus shapes and the bulk meniscus height also changes. Furthermore, a three-dimensional tomographic image

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is also reconstructed from the total of 128 projection images taken  $1.4^\circ$  apart in which the Li had already cooled and solidified.

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Neutron radiography; Heat pipe; Lithium; Neutron Tomography; Liquid metal

## 1. Introduction

The US Department of Defense is currently developing hypersonic technologies for use in global strike vehicles [1]. The Air Force Research Laboratory is maturing these technologies for the implementation in a flight vehicle capable of deployment thousands of miles from the target [2]. Large aerothermal heating in hypersonic flight conditions demands cooling for the leading edges of the vehicle. High-temperature heat-pipe-cooled-leading edge (HPCLE) technology using liquid metal working fluids has shown promise as an effective passive technique for meeting these demands [3].

High-temperature heat pipes are capillary driven, two phase heat transfer devices capable of passively providing high thermal fluxes which are needed to cool the leading edges of hypersonic vehicles. In general, heat pipes are sealed tubes which are evacuated and filled with a working fluid. The heat pipe is heated in the evaporator region, the heated working fluid travels through an adiabatic middle section, and is cooled at the condenser. During normal operations, the working fluid will undergo a phase change at the evaporator and, due to a pressure drop, travel along the pipe. As the vapour condenses, it is drawn back to the evaporator region by capillary pressure provided through an interior wicking structure. Working fluids are selected based on the desired temperature range of the heat pipe with alkali metals often used for high-temperature applications [4].

To characterize the mass transport phenomenon inside a high-temperature heat pipe, it is desirable to image the fluid movement. The metal shell used in the construction of liquid metal heat pipes makes traditional methods of imaging inadequate. However, the relatively small neutron cross section of refractory metals, such as Mo or Nb, can make distinguished shadow of liquid metal coolant (Li) inside. Neutron radiography is a non-destructive evaluation (NDE) technique well suited for many applications where traditional methods are inadequate. The Lambert-Beer law of attenuation describes the neutron beam intensity after passing through an object:

$$I = I_0 e^{-N\sigma t} \quad (1)$$

where  $I$  is the intensity after attenuation,  $I_0$  is intensity before attenuation,  $N$  is the atomic number density,  $\sigma$  is the element's cross sectional area due to scattering and absorption, and  $t$  is the thickness of the element.

The cross section for neutron beam attenuation has no simple relation to its atomic number and can change between isotopes. For instance, the thermal neutron scattering from hydrogen (82.36 barn; 1 barn =  $10^{-24}$  cm<sup>2</sup>) is about 11 times stronger than that from deuterium (7.64 barn), as schematically shown in Fig. 1. Materials with large cross sections are well suited for imaging because of their more distinguished shadows. Neutron beam lines are described by their collimation ratio and fluence rate. The collimation ratio is the ratio of the beam length ( $L$ ) after the aperture to the size of the aperture ( $D$ ) with the spatial resolution increasing for higher  $L/D$  ratios. However, the fluence rate decreases as  $(D/L)^2$ . This results in increased exposure times for higher spatial resolutions [5].

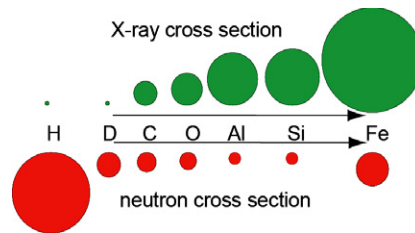


Fig. 1. Neutron cross sectional areas of different atoms in comparison with X-ray cross sectional areas [6].

Neutron radiography has been used to characterize fluid transport previously. In neutron radiography experiments using proton exchange membrane fuel cells, water transport was visualized through aluminium and carbon demonstrating the ability to penetrate some metals [7]. Additionally, fluid dynamics in oscillating heat pipes was captured at low resolutions with 30 Hz to 100 Hz frame rates [8, 9]. These experiments were successful in imaging fluid movement in metal environments without disruption of the thermal properties or fluid movement.

In this paper, a preliminary heat pipe radiography experiment has been performed on the BT-2 beam line at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland using a Ni-Na heat pipe at frozen ambient conditions. After successful demonstration of feasibility of neutron imaging, the CG-1D beam line at the High Flux Isotope Reactor (HFIR) of Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee has been used to image the operation of a high-temperature Mo-Li heat pipe for the first time up to steady state operation at approximately 900°C. Additionally, a three-dimensional tomographic reconstruction of the Mo-Li heat pipe working fluid has been achieved.

## 2. Experimental setup

Neutron radiography during high-temperature heat pipe operation was performed on a cylindrical, gravity assisted Mo-Li heat pipe 25 cm in length with an external diameter of 3.5 cm. This heat pipe has a square cross section width of 0.875" (22.2 mm), with four inside corner radii of 0.125 mm along the length of the pipe. It has been evacuated, backfilled with 10 g of Li, and sealed. Due to the oxidation of Mo at high temperatures, it was necessary to run the heat pipe in a vacuum vessel (Fig. 2). This was constructed from 304 stainless steel with 1/8" (3.18mm) wall thickness around the heat pipe, and multiple ports were installed for a vacuum pump, pressure gauge, heater power supply wires, and four thermocouples. The heat pipe was placed in the center of the vacuum vessel on an alumina ( $\text{Al}_2\text{O}_3$ ) bottom for insulation and heated using a Mo resistance wire heater wrapped in alumina fish spine beads. The wire heater covered the bottom 80 mm of the heat pipe, and four Type K thermocouples were attached along the heat pipe at 80 mm, 120 mm, 161 mm, and 198 mm from the bottom of the pipe. Surrounding the heat pipe, resistance wire heater, and the thermocouples were 8 layers of Mo foil to serve as radiation shielding.

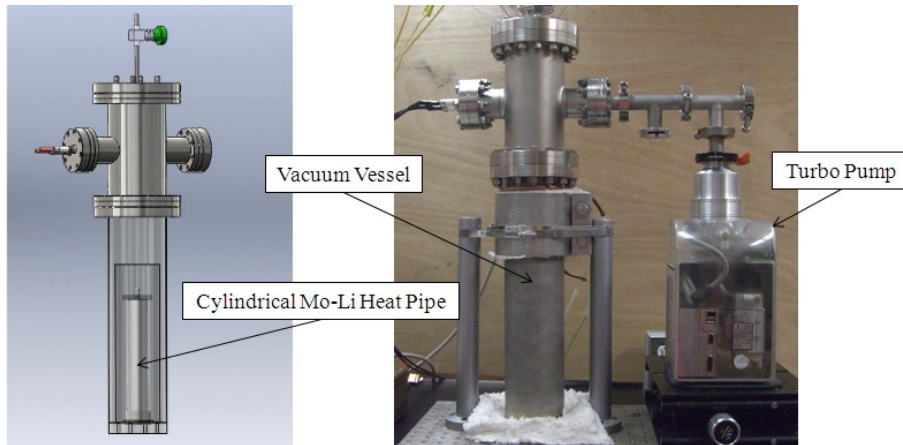


Fig. 2. Vacuum vessel used for testing of cylindrical Mo-Li heat pipe. The heat pipe is located in the lower section.

### 3. Results

Preliminary neutron radiography testing was performed at NIST using a 150 mm long nickel alloy heat pipe with Na working fluid and a 3 mm by 10 mm cross section (Fig. 3). This heat pipe remained at ambient frozen conditions to determine the transmission,  $T = I/I_0$  from Eq. 1, where  $\sigma = 3.81$  barn for Na. The exposure time for one image was 100s. The transmission calculated for 3 mm thick solid Na slug was  $T = 0.97$  or a 3% contrast with the background. The low contrast for Na needed longer exposure time and binning of the image data. Changing the working fluid to Li for successive testing was based on these findings as Li has a higher neutron attenuation cross section than Na.

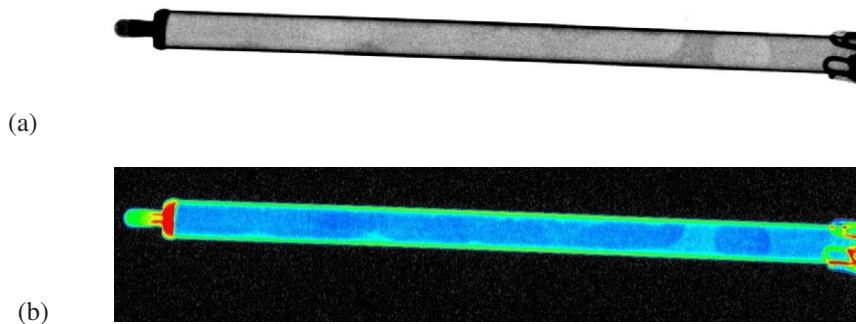


Fig. 3. (a) Neutron transmission image of solid Na in a nickel 201 heat pipe from a 100 s exposure and (b) the corresponding false color image [5].

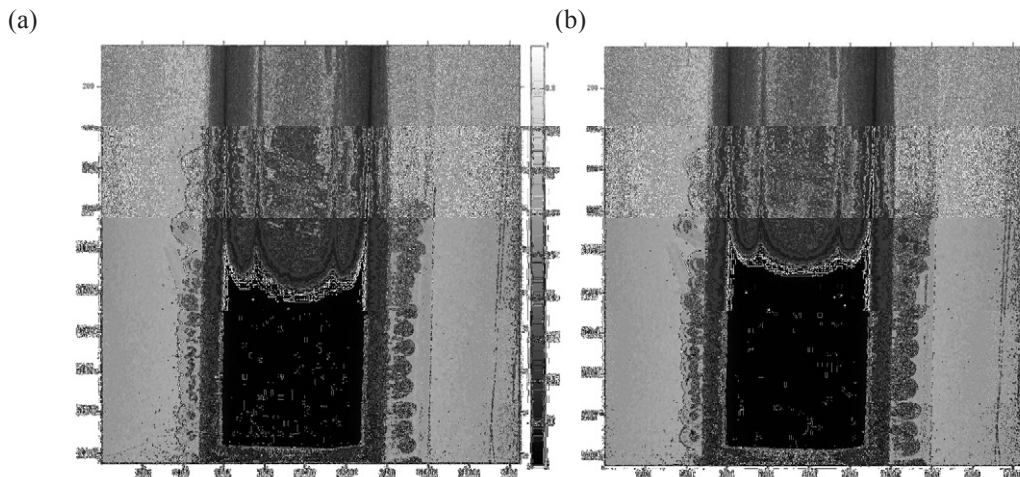
In order to ensure the feasibility of neutron radiography, a ring-shaped Mo-Li heat pipe (11.6 cm outside diameter and 1.9 cm tube diameter) was imaged first at the ORNL campus. Note that because of the limited viewing window size, four separate images were recorded and later digitally integrated to conform to a full image as shown in Fig. 4. Additionally, open beam and dark field images were taken for normalization to further enhance the image resolution and quality. The darker region in the right half of

the heat pipe is from the attenuation due to solid Li with the remainder of the pipe empty. The stand used to hold the heat pipe is seen faintly in the background along with the fill tube at the top of the picture.



Fig. 4. Torus shaped Mo-Li heat pipe partially filled with the Li.

Operational images of the cylindrical Mo-Li heat pipe show a distinct change in the bulk meniscus level and the meniscus shape (Fig. 5). A time lapse reconstruction shows the response of the Li to temperature variations. Fig. 5 (a) shows the heat pipe in the frozen ambient condition, 22°C, before heat is applied with the transmission scale and Fig. 5 (b) shows the heat pipe while operating at an average evaporator region temperature of 893°C as measured from the thermocouple located 80 mm from the bottom of the heat pipe. As the temperature of heat pipe is increased, the bulk Li level gradually increases. The average Li level rise between heat pipe operations at 22°C and 893°C is 9 mm, as the lighter areas are representing the meniscus rises in Fig. 5 (c). This trend continues during the temperature oscillations occurring after the heat pipe reached 900°C, although no unsteady operations are obvious. The capillary rises of the liquid lithium along the four corners are reduced due to the lower surface tension with increasing heat pipe temperature and this increases the Li return making the menisci rise. Additionally, some of the Li level change can be attributed to density changes in the Li as it is heated causing a volume expansion.



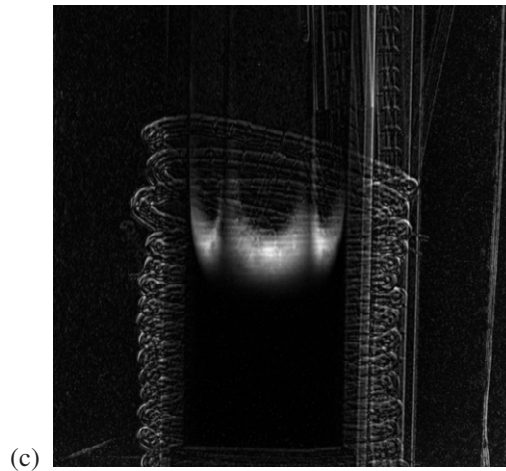


Fig. 5. Cylindrical heat pipe at (a) 22°C with the neutron transmission scale and (b) 893°C along with (c) a comparison of the two images. In (c) the lighter areas are representative of changes between (a) and (b).

Tomographic imaging of the cylindrical heat pipe was performed by taking images in 1.4° increments for a total of 128 images. The heat pipe was in the frozen state for this after the high-temperature experiment was completed as Li movement would prohibit tomographic reconstruction. Shown in Fig. 6 is an image of the tomographic reconstruction of the frozen Li within the cylindrical Mo-Li heat pipe. As expected, the Li is pooled in the bottom of the pipe, and dramatically rises along the four 90° corners of extremely small capillary radii (0.125 mm). Analysis of the acquired neutron images of an operational high-temperature heat pipe and the tomographic image in its frozen state will help characterize the Li transport phenomenon and provide a basis for future tests.



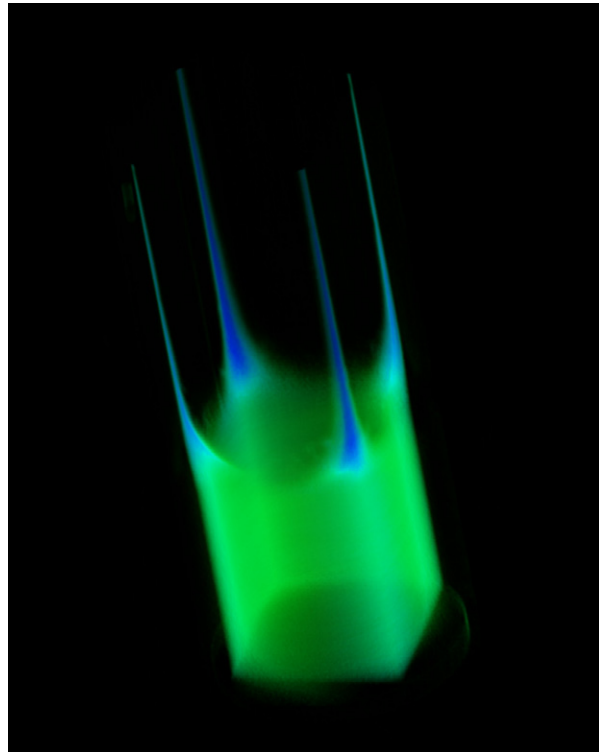


Fig. 6. Tomographic reconstruction of Li within the cylindrical Mo-Li heat pipe. Capillary pressure holds the Li in the 90° corners that form the wicking structure for this gravity assisted heat pipe.

#### 4. Concluding Remarks

Neutron radiography is a viable approach to characterizing Li behavior in a high-temperature heat pipe. Steady operations were achieved from 22°C to 900°C resulting in Li meniscus height and shape changes providing a foundation for future testing. Specifically, this Mo-Li heat pipe will be tested during unsteady operations using asymmetric heating loads. To capture unsteady operations, it will be necessary to decrease the exposure time for each image. Additionally, quantification of Li thickness along the wicking channels can be used to further the understanding of the different phases of high-temperature heat pipe operations.

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